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Woody Fuel and Duff Consumption by Prescribed Fire in Northern Idaho Mixed Conifer Logging Slash

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RESEARCH SUMMARY

Experimental burns were conducted on 36 plots in mixed conifer logging slash in northern Idaho to investigate consumption of duff and woody fuel. Prescribed fires were conducted in spring and fall, in YUM (yarded unmerchantable material) and non-YUM clearcuts and seedtree cuts. Preburn and postburn fuel loadings were measured, and fuel moistures were sampled shortly before burning. Preburn duff depth ranged from 1.2 to 2.6 inches. Preburn woody fuel loadings ranged from 28 to 86 tons/acre. Sixty-four percent of the duff was consumed. Most of the small woody fuel was consumed, along with an average of 15.5 tons/acre of large woody fuel. Postburn mineral soil exposure averaged 66 percent. Residual loading of large woody fuel averaged 31 tons/acre.

Methods for predicting duff and woody fuel consumption are reported. For predicting percentage of duff reduced, the best independent variables were shallow duff moisture content and unit average diameter reduction of large woody material. For predicting duff depth reduction, the best independent variables were average duff moisture content and preburn duff depth. Diameter reduction of large woody fuel was best predicted using moisture content and average prebum diameter as independent variables.

Guidelines are included for fire prescription development. These include recommendations for amounts of fuel to retain and to consume and discussion of tradeoffs in setting fire objectives. Equations are presented for computing moisture contents for desired levels of consumption.

CONTENTS

	Page
Introduction	1
Objectives	2
Study Area and Design	2
Data Collection	3
Analysis	5
Results and Discussion	7
Preburn Fuel Characteristics	7
Moisture Contents at Time of Bum	11
Consumption and Postburn Characteristics	11
Management Considerations	16
Prescription Development	18
Prediction Equations	19
References	19
Appendix 1: Listing of Data Values by Unit for Key Variables	21
Appendix 2: Error in Fuel Moisture Content Estimation	22

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INTRODUCTION

Prescribed fire is used in natural resource management to accomplish a variety of objectives. It is often used after timber harvest to reduce fire hazard and prepare the site for regeneration, either natural or planted.

Duff consumption and mineral soil exposure are primary objectives of many prescribed fires in Northern Rocky Mountain forests when encouragement of natural regeneration is desired. Burned or mineral soil seedbeds are preferred substrates for successful germination and early survival of many tree species (Haig and others 1941; Minore 1979).

Downed dead woody fuel consumption is often a critical variable to consider when planning a prescribed fire. The consumption of downed woody fuels affects the amount of duff consumed (Ottmar and others 1985) and consequently the amount of mineral soil exposed. Woody fuel consumption also determines many secondary effects. Other things being equal, the more fuel consumed the greater the heat impact on the site. The amount of heat transmitted downward to the duff and soil often governs the extent to which on-site plant parts will revegetate the burned area, and thus impacts postfire species composition and wildlife habitat. Fuel consumption is also important for reducing subsequent fire hazard and for removing physical impediments to tree planting. Slash removal also facilitates big game passage through the area.

On the other hand, managers may wish to limit consumption of duff and large woody fuel in order to limit the production of smoke from the prescribed burn, protect the site from erosion, provide protection for planted trees, and maintain long-term site productivity and nutrient cycling. Smoke production increases with fuel consumption. Erosion is reduced by retaining an organic mantle and large woody pieces on the site. Work by Harvey and others (1987) has demonstrated the roles of duff and large woody fuel in maintaining site productivity. Duff is important in storing nitrogen and absorbing cations. Large woody material is important because it is a site for nitrogen fixation and the source of future soil wood—an important soil component.

Because of these considerations, managers attempt to remove specified amounts of fuel and also retain desired amounts of residual organic material. Consumption of fuels and retention of organic material can be described in several ways. Duff consumption is often described as depth reduction, percentage depth reduction, and percentage mineral soil exposure. For evaluating smoke emissions and nutrient capital, depth reduction is the appropriate expression because it describes actual amounts and can be converted to weight if duff bulk density is known. Percentage duff reduction is commonly used to describe fire prescription targets. It must be applied to preburn depth or loading to estimate actual amounts of duff removed or retained. Percentage mineral soil exposure relates to regeneration potential, seedbed quality, and vulnerability to erosion. Objectives and constraints of prescribed fire can often be expressed as desired or acceptable levels of percentage mineral soil exposure.

Consumption of woody fuel is often described as percentage of preburn fuel quantities consumed, especially for evaluating prescribed fire effects and designing fire prescriptions. It may be predicted initially as average diameter reduction of woody pieces and then converted to percentage volume reduction or fuel loading reduction.

Fuel and duff reduction equations have been developed from experimental fires to aid in writing prescriptions to meet fuel management goals in the western larch/Douglas-fir type of western Montana (Brown and others 1985; Norum 1977; Shearer 1975),

and in the coastal Douglas-fir type in the Pacific Northwest (Little and others 1986; Ottmar and others 1985; Sandberg 1980). None had been developed in the mixed conifer types of northern Idaho, nor did experimental data exist for testing the accuracy of other models. For the purposes of this discussion, the mixed conifer types of northern Idaho include the following forest cover types described by the Society of American Foresters (Eyre 1980): western larch (212), grand fir (213), and western white pine (215).

OBJECTIVES

In recent years, changing constraints on smoke production and site protection have created a need to better understand fire effects, particularly woody fuel and duff consumption, and to develop alternatives for meeting fuel treatment and site preparation goals. This paper reports a study designed to quantify and predict fire effects resulting from several fire treatments in northern Idaho mixed conifer logging slash.

The objectives of this study were:

1. Characterize fuels in seedtree and clearcut harvest systems following YUM (yarding of unmerchantable material) and no-YUM treatments in this forest type.
2. Describe first-order fire effects, including fuel consumption, mineral soil exposure, fire severity, and reduction in herbaceous cover and shrub cover following spring and fall burning in these sites.
3. Test the accuracy of duff consumption equations derived from prescribed fire studies in other western forest types.
4. Determine diameter reduction of large fuels as related to moisture content, degree of rot, and interaction of adjacent pieces.
5. Provide guidelines to managers planning prescribed fires in this forest type.

STUDY AREA AND DESIGN

The study area is a series of small harvesting units on the Deception Creek Experimental Forest near Couer d'Alene, ID (fig. 1). The Experimental

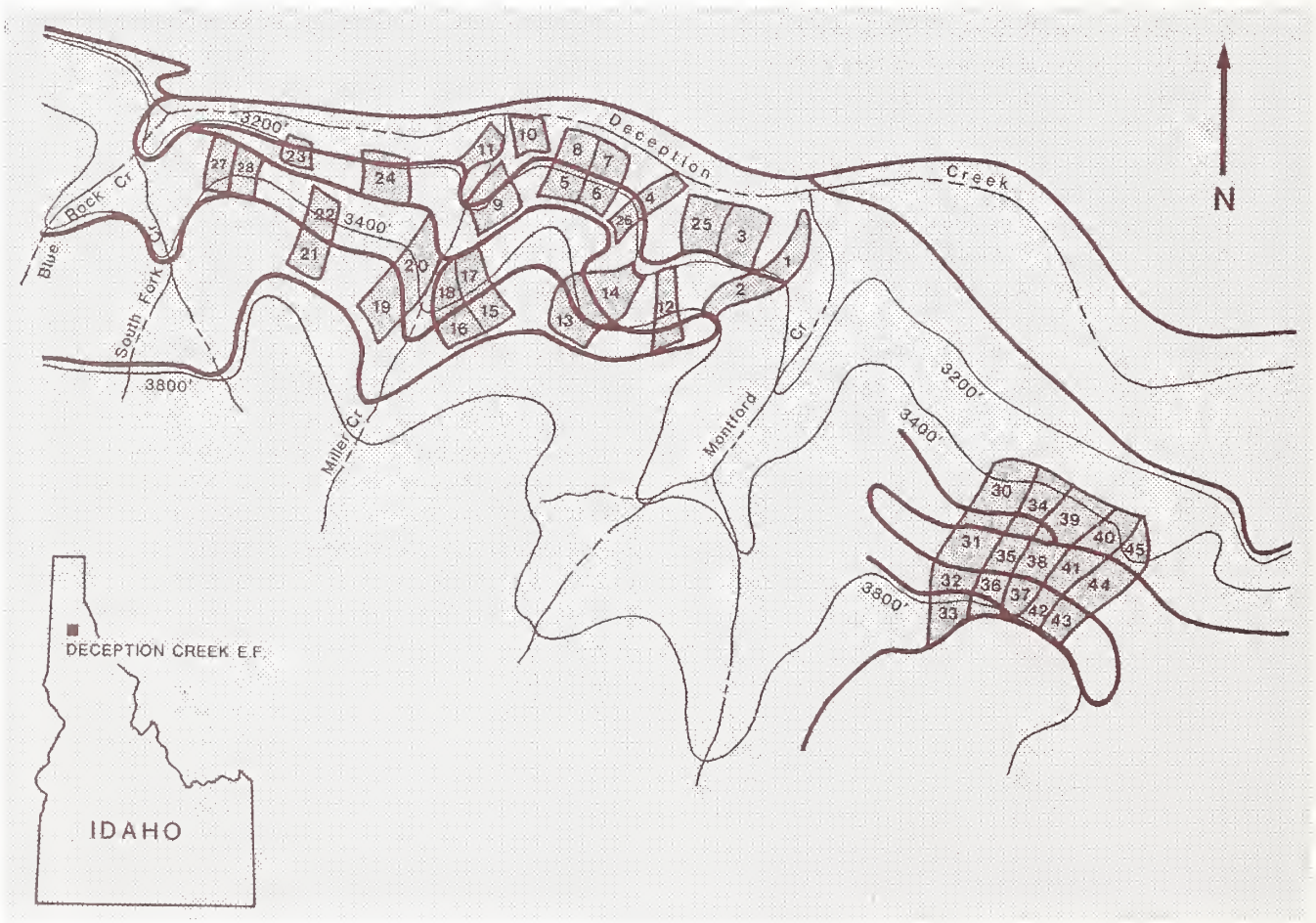

Figure 1—Location of the Deception Creek study area and the 44 experimental units.

Forest is part of the Idaho Panhandle National Forests in the Fernan Ranger District. The study site is on a steep (50 to 80 percent), north-facing slope at 3,000 to 4,000 ft elevation. Precipitation averages 60 inches annually; about 25 percent of it is snow, which usually lasts from November to late April (Finklin and Fischer 1987).

Two groups of experimental units were established: the first group was located on a series of strip clearcuts west of the Montford Creek natural area (units 1 to 28), and the second group on alternating clearcut-seed tree strips east of the natural area (units 30 to 45). Units were 1 to 2 acres in size.

Before harvest, the units were occupied by grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl.), western white pine (*Pinus monticola* Dougl. ex D. Don), and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.); smaller amounts of western larch (*Larix occidentalis* Nutt.) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) were present. Total standing volume before harvest ranged from 5,610 to 11,510 ft^3/acre (29 to 57 M bd ft/acre). Dead western white pine, killed by blister rust and bark beetle attacks, comprised 10 to 30 percent of the total standing volume. The habitat type in the area was *Tsuga heterophylla/ Clintonia uniflora-Clintonia uniflora* phase (Cooper and others 1987).

Units were harvested in the winters of 1982 to 1983 and 1983 to 1984. A skyline yarding system was used. In 12 of the clearcut units a YUM treatment was applied: unmerchantable material greater than 6 inches in diameter was yarded to the tops of the units and made available to firewood cutters, resulting in lighter woody fuel loadings and additional duff and soil disturbance (fig. 2). Units were burned in spring (June) of 1985 and 1986 and late summer/fall (August and September) of 1984 and 1985 to provide a range of fuel moisture conditions. The fires were strip head fires ignited using propane torches (fig. 3). Burns were conducted by Fernan Ranger District personnel. Eight of the units were reserved as unburned controls for studies (not described here) on root rot and regeneration. Unit treatments are summarized in table 1.

DATA COLLECTION

In each unit, 20 sample points were systematically placed and permanently marked. At each point, small (less than 3 inches in diameter) and large (3 inches and greater in diameter) downed woody fuels were inventoried along a randomly oriented transect (Brown 1974). Diameter classes were one-fourth to 1 inch tallied along a 6-ft segment; 1 to 3 inches, along a 10-ft segment; and

Figure 2—"YUM" pile at the top of a clearcut unit.

Figure 3—An early evening burn.

Table 1—Unit harvest and burn treatments by unit number

	June burn				August/September burn				Unburned control			
YUM	9	12	13	17	3	5	6	24	1	10	11	26
No-YUM	7	8	14	15	19	20	25	32	2	4	22	23
	16	18	21	27	33	36	37	42				
	28	30	31	34	43							
	35	38	39	40								
	41	44	45									
Wired for	8	14	15	16	19	20	25	36				
diameter	18	21	27	28	37	42						
reduction	34	35	40	41								

greater than 3 inches, along a 50-ft segment. Large pieces were characterized as being sound; rotten, with brown cubicle rot present; or rotten.

Quantities of 0- to ¼-inch woody material were estimated as 55 percent of the ¼- to 1-inch loading in the YUM units, and 44 percent in the no-YUM units. These percentages were determined by collecting all material less than 1 inch on fifteen 0.5- by 0.5-m plots in each of three YUM units and two no-YUM units, separating the 0- to ¼-inch from the ¼- to 1-inch material, and ovendrying and weighing the samples. Variation was large among these samples. Coefficient of variation was 53 percent for samples from YUM areas, 91 percent for samples from no-YUM areas.

Depth of duff (02 horizon) was measured at three locations along each transect and categorized as derived from rotten wood or litter.

Two microplots were established at each sample point. These microplots were nominally 1 m square and were marked with large spikes driven into the

soil at each corner, their heads flush with the duff surface. The spikes served to mark the microplots and were also used to measure duff depth reduction from fire. On each microplot, percentage cover of duff, mineral soil, and large (>3-inch diameter) woody material was estimated. Percentage cover of herbaceous plants, subshrubs, and shrubs was also estimated. Sample point layout is pictured in figure 4.

In 18 of the no-YUM plots, 60 logs were circled with wire for diameter-reduction measurement (Hedin and Turner 1977) (fig. 5). Logs selected were at least 3 inches in diameter. The first three logs intersected by each of the 20 fuel transects were selected. Species, presence or absence of bark, degree of rot, distance from the ground, and distance from the nearest large woody piece were recorded. Degree of rot was determined by judging pieces as being either sound throughout, rotten outside and sound inside, sound outside and rotten inside, or rotten throughout.

Immediately before the burns, moisture contents of duff, 0- to ¼-inch twigs, and ¼- to 1-inch twigs were sampled. Because the duff was generally shallow and undifferentiated into distinct strata, it was impractical to separate it into upper and lower layers for moisture sampling. Instead, we sampled moisture of the usually shallow layer of litter-derived duff and moisture of deep pockets of rotten wood.

On units with wired logs, a slice approximately 1 inch wide was sawed from each wired log within 1 to 3 ft of the wire for moisture content determination (fig. 6). To establish the moisture-sampling procedure, moisture content was sampled at the top, bottom, center, and sides of six logs by extracting 2- by 2-inch pieces from slices taken at 1- and 2-ft intervals along each log. Moisture content was reasonably uniform over horizontal distances of 1 to 3 ft, thus the moisture content at the wire seemed adequately represented by the moisture content of the slice. Moisture content within a slice varied considerably within some logs (fig. 7). Thus, an entire slice was collected to represent piece moisture content. All samples were ovendried for moisture content determination.

Temperature, precipitation, and relative humidity were recorded on site with a remote automatic weather station. National Fire Danger Rating System (NFDRS) 1,000-hour fuel moisture (Deeming and others 1977) and adjusted 1,000-hour fuel moisture (Ottmar and Sandberg 1983) were computed from daily maximum and minimum temperatures and relative humidities and precipitation duration.

Postburn measurements included a reinventory of the woody fuel transects. The length of transect traversing unburned areas was recorded. Measurements of duff consumption and residual duff depth were taken at each of the duff spikes. Microplots were reassessed, and coverage estimates of mineral soil, unburned duff, charred duff, and woody material were made. Each microplot was assigned a depth-of-char rating as defined by Ryan and Noste (1985). Wires on the logs were measured to determine preburn circumference; then were cinched up and measured to determine postburn circumference.

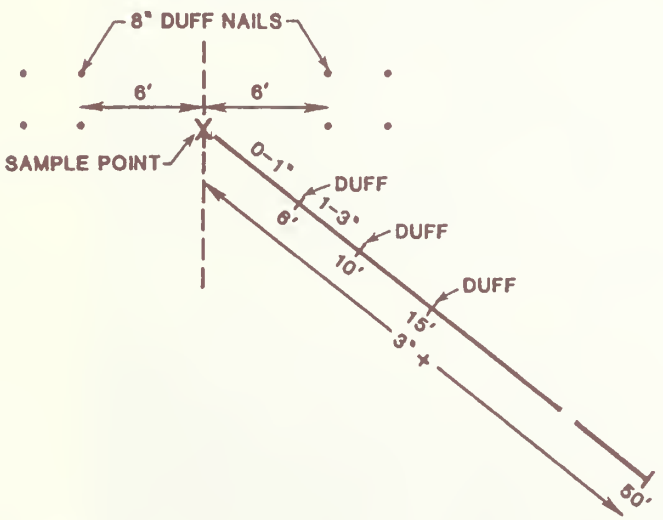

Figure 4—Sampling scheme at each of the 20 sample points on an experimental unit.

ANALYSIS

Fuels and fuel consumption were characterized by treatment, fuel consumption and mineral soil exposure were compared with that predicted by previous studies, and prediction equations were developed for estimating fuel consumption and mineral soil exposure using multiple linear regression. Data were screened for nonlinearity and heteroscedasticity by examination of plotted values. Predicted consumption from previous studies was compared to observed consumption by examining the average deviation or bias and the root mean square of deviations. Previous studies included Sandberg (1980) and Little and others (1986) in Douglas-fir/western hemlock clearcuts, Ottmar and others (1985) in Douglas-fir/western hemlock partial clearcuts, Brown and others (1985) in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.)/Douglas-fir/western larch partial cuts, clearcuts, and undisturbed stands, and Harrington (1987) in undisturbed ponderosa pine.

Figure 5—Log being wired for diameter-reduction sampling.

Figure 6—Moisture sampling of large woody material.

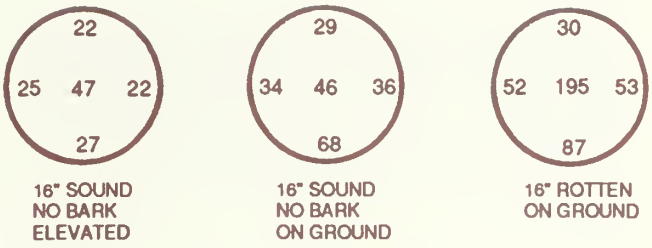

Figure 7—Percentage moisture content at top, bottom, center, and sides of three selected logs. The moisture contents are averages of five measurements taken at 1-, 2-, 3-, 5-, and 7-ft intervals. Coefficients of variation ranged from an average of 22 percent for the measurements at the top of the logs to 41 percent for the measurements at the bottom of the logs.

We defined mineral soil exposure as duff depths less than 0.4 inch (1.0 cm), and calculated percentage of mineral soil exposed as the percentage of spikes with residual duff depth less than 0.4 inch. This criterion was chosen because residual duff less than this depth is not usually considered to be an obstacle to natural regeneration (DeByle 1981) and because we expected further decomposition of the residual duff to take place. Consumption of duff by type of material was evaluated by classifying the data from the spike measurements as litter-derived or rotten wood, assuming that if the preburn duff depth was greater than 3.5 inches the material was rotten wood. This classification was chosen because it resulted in 14 percent of all spikes occurring in rotten wood, which agreed with the preburn duff data from fuel transects. Pre- and postburn woody fuel loadings were computed from transect intersect data (Brown 1974). Consumption of large fuels was also calculated from the change in circumference of wired logs as diameter reduction and percentage of volume reduced. Unit average volume reduction was calculated as the sum of cross-sectional areas reduced by burning, divided by the total cross-sectional area of all wired logs on a plot.

RESULTS AND DISCUSSION

A listing of data values for important variables by unit is included in appendix 1. Preburn fuel loadings, moisture contents, and fuel consumption are reported for duff and woody fuel.

Preburn Fuel Characteristics

Duff—Forest floor characteristics are shown in figure 8. The deep rotten wood covered an average of 13 percent of the forest floor. Twenty-three percent of the area had preburn duff depths less than 0.4 inch. Seven percent had no duff (based on spike data). The remainder of the forest floor (47 percent) was covered with litter-derived duff 0.4 inch or greater in depth. Preburn duff depth at Deception Creek averaged 1.5 inches, which is typical of duff profiles in the cedar/hemlock type and warm moist habitat type group of northern Idaho (Brown and See 1981). The duff consisted

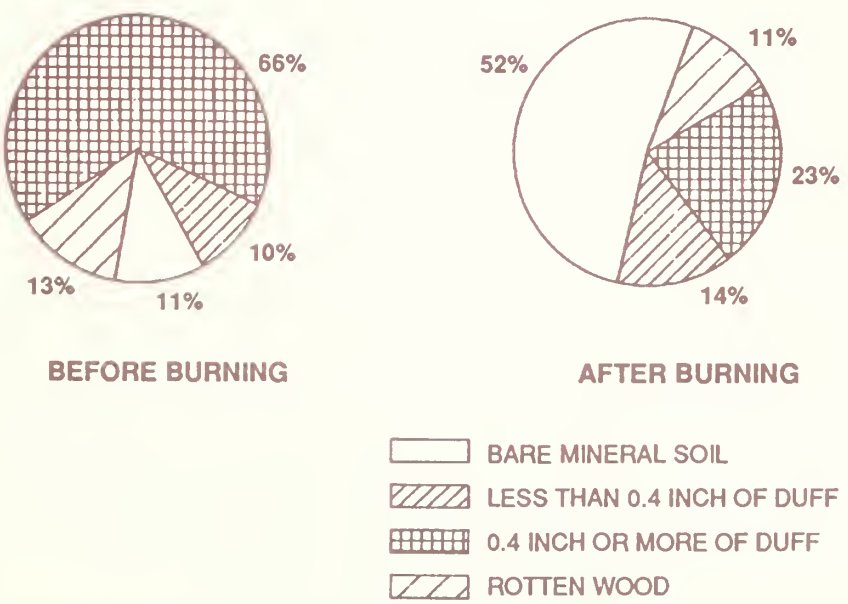

Figure 8—Composition of the forest floor before and after burning.

of a shallow (mean = 0.8 inch) layer of decomposing litterfall interspersed with pockets of rotten wood averaging 5.3 inches deep (fig. 9). Bulk density of the litter-derived duff was 5.0 lb/ft^3, excluding non-organic soil mineral material. Bulk density of the pockets of rotten wood was estimated to be 9.4 lb/ft^3, based on data from similar stands. Preburn duff loading averaged 21.1 tons/acre of organic material (based on the measurements at the duff spikes). Mineral content of the litter-derived duff averaged 44.8 percent based on ashing of the duff samples in a muffle furnace to remove all carbon.

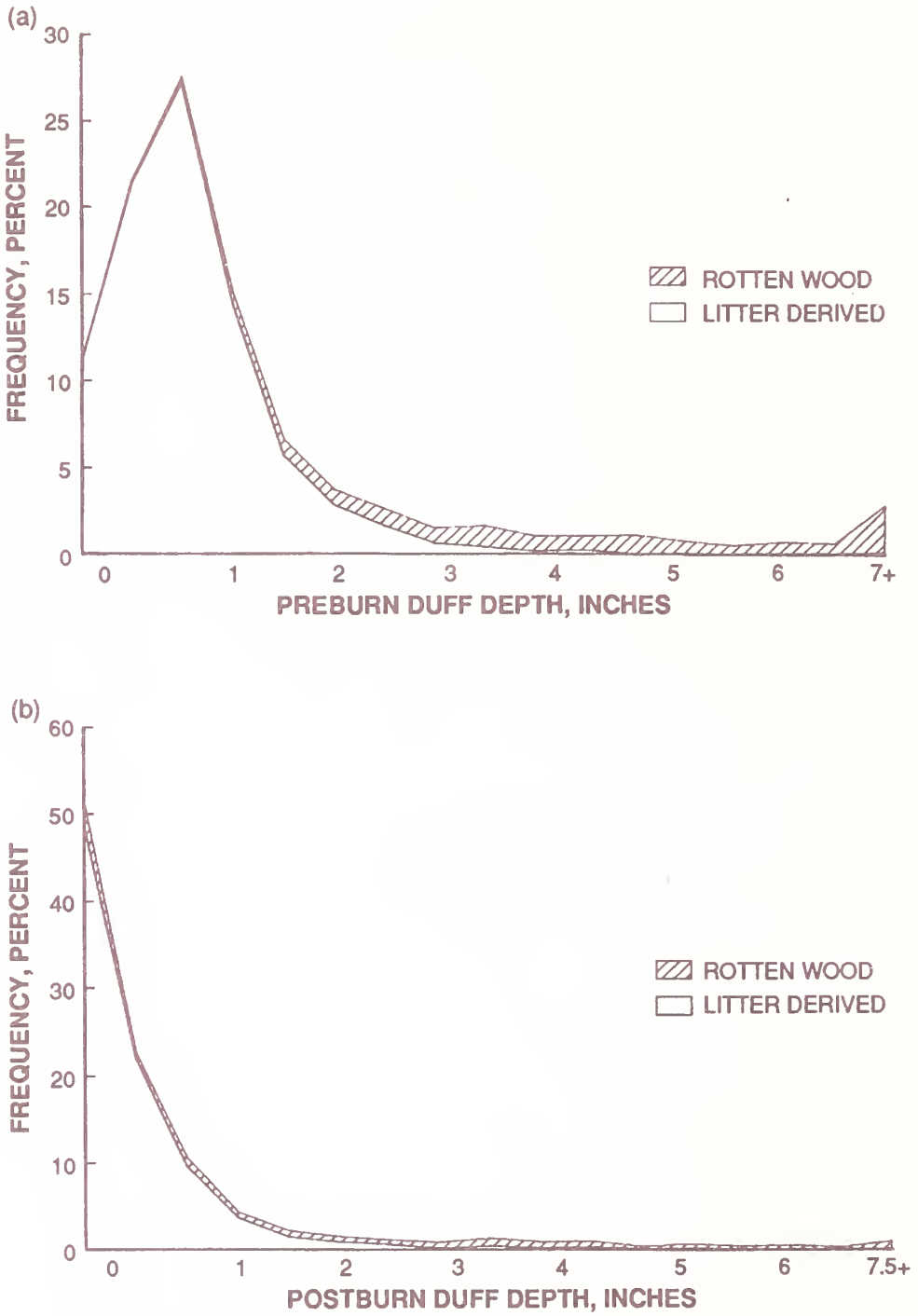

Figure 9—Percent frequency of duff depths for litter-derived duff and rotten wood, before (a) and after (b) burning.

Preburn duff depth as measured along the transects before the burns was significantly less than that measured on the spikes after the burns as the sum of the exposed length along the spike and the residual duff. The difference between spike and transect depths averaged 0.35 inch. This difference was significant at a probability level of 0.002, using a paired T-test to compare unit means. Because unit averages were based on 60 measurements along the transects and 160 spike measurements, this difference seems to reflect a real sampling bias rather than insufficient sample size. Evidently material at the bottom of the duff profile, not recognized as duff in the preburn measurements, was being consumed and thus included in the spike measurements.

Preburn duff depth did not differ significantly between harvest areas or between postharvest treatments (YUM/no-YUM).

Woody Fuel—Preburn downed woody fuel loadings averaged 58.5 tons/acre and ranged from 28 to 86 tons/acre. Rotten pieces averaged 21 percent of the volume of the 3+-inch class on the no-YUM units and 60 percent on the YUM units. The YUM treatment significantly reduced loading of large fuel (fig. 10) to an average of two-thirds the loading in no-YUM units. Small fuel loading was not significantly different between YUM and no-YUM.

Seventy-seven percent of the large pieces were sound, and 23 percent were rotten (table 2). Rotten pieces had greater average diameter than sound pieces (fig. 11). Bark was present on 60 percent. Species was readily evident on 69 percent of the pieces; most of the pieces were western hemlock, but most of the volume was white pine. Although only 13 percent of the pieces were 15 inches and greater in diameter, they accounted for 44 percent of the volume. Distance to the soil averaged

Table 2—Characteristics of large woody fuel

Characteristic	Pieces	Volume
	- - - Percent - - -	
Species:		
Grand fir	12	13
White pine	20	29
Western hemlock	33	24
Other	4	3
Unknown	31	31
Quality:		
Sound	77	73
Rotten	23	27
Rotten outside, sound inside	8	9
Sound outside, rotten inside	3	5
Rotten throughout	12	13
Brown cubicle rot	7	10
Other rot types	16	17
Presence of bark:		
Bark present on sound pieces	73	69
Bark present on rotten pieces	14	17

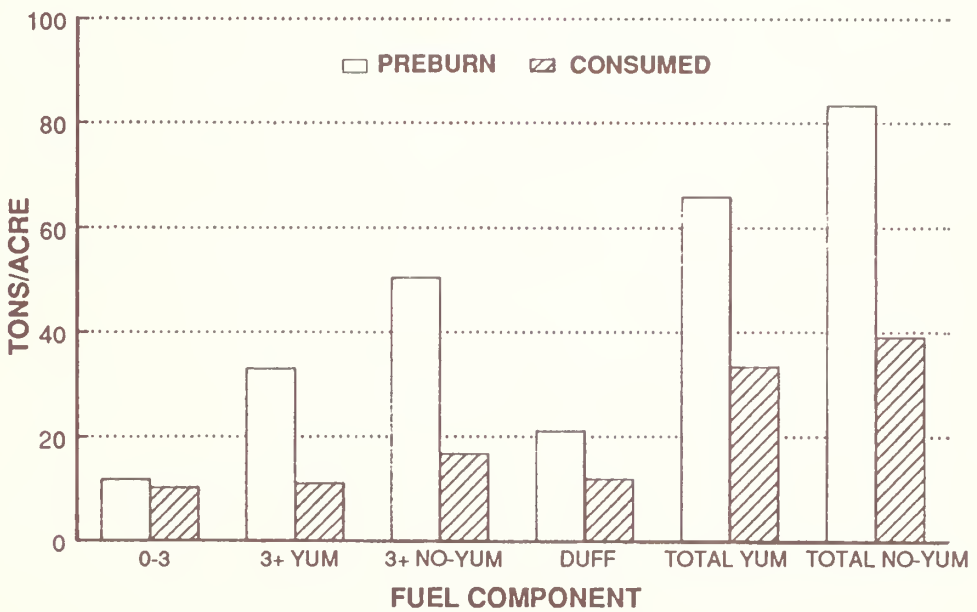

Figure 10—Average preburn fuel loadings and fuel consumption.

6.0 inches, with a median of 3.0 inches. Distance to closest neighbor averaged 23 inches, with a median of 17 inches.

Cover—Three percent of the area in the microplots was categorized as having mineral soil exposure before the fire. There was no difference in preburn mineral soil exposure between YUM and no-YUM units. The remainder was covered with organic material, including 15 percent coverage by down 3+-inch wood, 2 percent coverage by stumps, and the remainder duff or litter. Plant coverage was shrubs, 7 percent; subshrubs, 6 percent; and herbaceous plants, 27 percent.

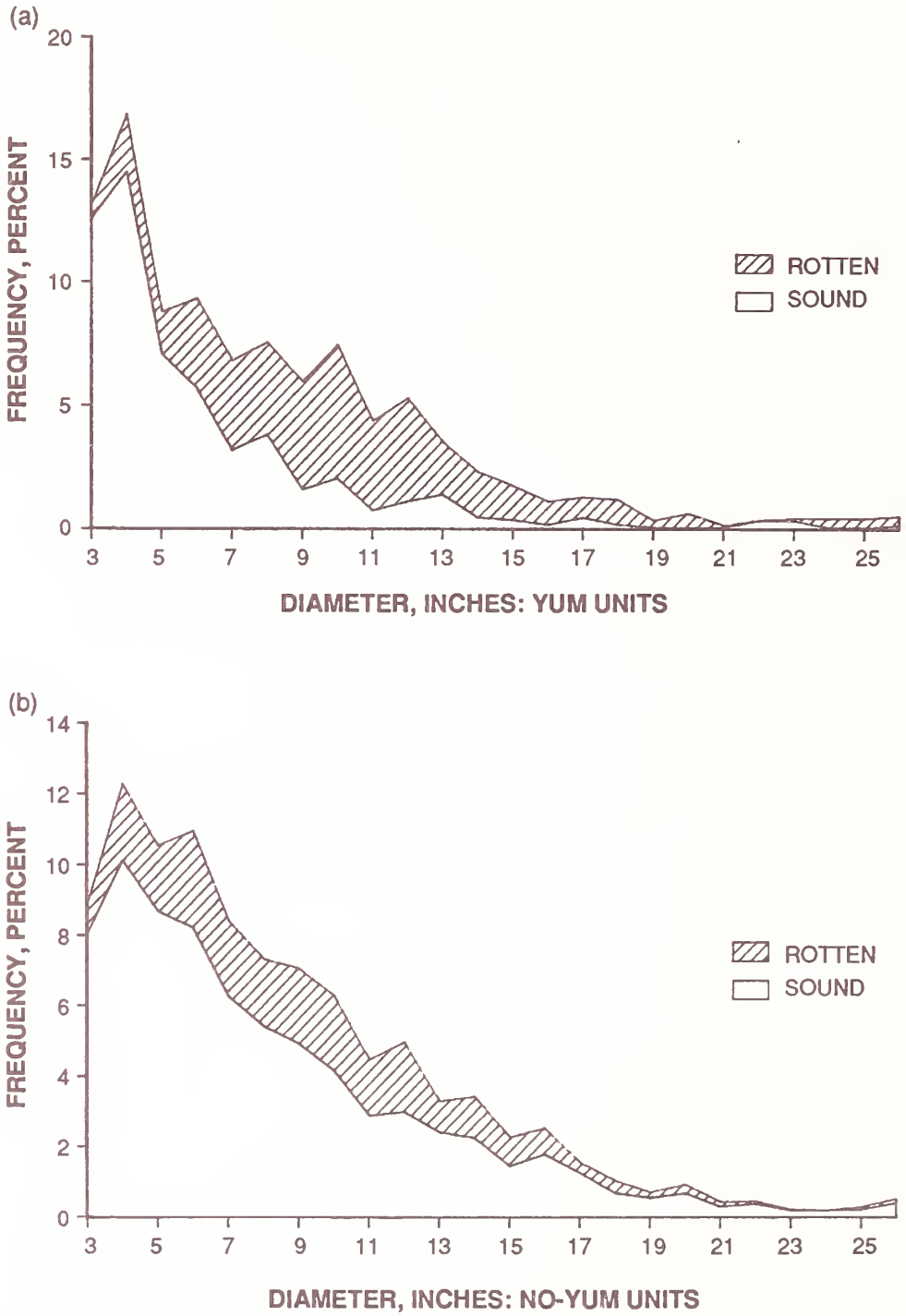

Figure 11—Diameter distribution of sound and rotten logs on YUM (a) and no-YUM (b) units.

Moisture Contents at Time of Burn

Moisture contents at burn time are summarized in table 3. The moisture content of the deep pockets of rotten wood was much greater than of the litter-derived duff layer. In the fall of 1984, when only 0.3 inch of rain had been recorded since the end of June, moisture contents over 200 percent were still being observed in these pockets. Average moisture content of shallow duff in spring burns was less than fall burns, while average moisture content of the deep rotten wood was greater for spring burns than fall burns. The shallow layer evidently dried quickly in the long spring days, while the deep, saturated pockets of rotten wood responded much more slowly to seasonal drought. Moisture content of the entire duff profile was calculated as a weighted average of shallow duff and deep rotten wood moisture, weighted by proportion of area covered by duff type. Moisture content of rotten woody pieces was notably greater than that of sound pieces.

Relationships between percent error and sample size for moisture sampling of the various fuel components are shown in appendix 2. Large sample sizes are required to estimate moisture contents precisely when the variation is great.

Residence time for continuous flaming at an observation point was 4 to 12 minutes. Flame heights were controlled by slow strip ignition. Typical flame heights were 1.5 to 10 ft.

Consumption and Postburn Characteristics

Duff—More than half of the duff on the units was burned (table 4)—an average of 64 percent of the volume and 60 percent of the loading, or 13.7 tons/acre. Fifty-seven percent of the rotten wood duff and 75 percent of the litter-derived duff was consumed. No differences in duff depth reduction were observed between YUM and no-YUM treatments, even though the YUM process resulted in some disturbance of the duff and reduction of woody fuel loading. The median residual duff depth was 0 on most (56 percent) of the burned units, and exceeded 0.4 inch on only 2 units. Seventy-five percent of the residual duff loading was rotten wood. The residual rotten wood duff averaged 3.9 inches in depth, and residual litter derived duff averaged 0.6 inch.

Duff depth reduction and percentage of duff reduced were negatively correlated with shallow duff moisture (table 5) and entire duff moisture. They were not significantly correlated with the moisture content of the deep rotten wood or NFDRS 1,000-hour fuel moisture (Deeming and others 1977). Duff depth reduction was strongly correlated with preburn duff depth. Percentage of duff reduced was correlated with diameter reduction of large woody fuel, but duff depth reduction was not.

Percentage duff consumption observed at Deception Creek was greater than that predicted by most of the equations in the literature, using NFDRS 1,000-hour fuel moisture, lower duff moisture, humus layer moisture, preburn duff depth, and consumption of large woody material as independent variables (Brown and others, in press). It was predicted well by Brown's 1985 equation for sites in the Northern Rocky Mountains, when moisture content of the shallow duff layer was used for average duff moisture:

$$DR\% = 83.7 - 0.426\ ADM \quad (1)$$
$$(R^2 = 0.69,\ \text{s.e.} = 14.7)$$

where DR% = duff consumption, percent; and ADM = average duff moisture content, percent.

For the 35 burned plots, the average magnitude of the deviations between observed duff consumption and that predicted by this equation was 10.7 percent. The bias was only 1.5 percent.

Table 3—Moisture contents at time of burn, percentage by dry weight

Fuel	June			August/September			All average
	Mean	Min.	Max.	Mean	Min.	Max.	C.V.[1]
Litter-derived duff	16	10	32	30	18	40	54
Deep rotten wood	195	125	300	134	80	178	47
0-¼-inch	11	8	19	12	9	18	15
¼-1-inch	11	7	17	16	11	25	20
3+-inch sound	47	35	55	46	32	61	59
3+-inch rotten	83	50	111	65	55	81	76

[1]C.V. = coefficient of variation within a unit, S/X (100%).

Table 4—Preburn and residual fuel loadings and fuel consumption. Standard errors are in parentheses. All values are tons/acre except where noted

Number of plots	Fuel	Preburn		Residual		Consumed		Percent consumed	
				June					
[1]22	duff (inches)	1.90	(0.09)	0.66	(0.05)	1.24	(0.07)	64.7	(2.3)
22	duff	23.2	(0.6)	9.0	(0.6)	14.2	(0.7)	60.7	(2.6)
23	0-3-inch	11.4	(0.5)	1.4	(0.2)	10.0	(0.6)	86.9	(2.8)
4	3+-inch YUM	36.1	(7.2)	21.9	(4.4)	14.2	(5.0)	38.8	(8.3)
19	3+-inch no-YUM	47.9	(2.4)	33.1	(3.0)	14.8	(2.7)	30.5	(4.4)
4	total YUM	71.4	(8.8)	36.6	(5.1)	34.8	(8.2)	47.9	(7.0)
19	total no-YUM	82.5	(2.4)	40.4	(1.4)	42.1	(2.4)	50.6	(1.7)
				August/September					
13	duff (inches)	1.67	(0.10)	0.64	(0.09)	1.03	(0.09)	61.9	(4.1)
13	duff	21.6	(0.7)	8.8	(1.0)	12.8	(1.0)	59.0	(4.2)
13	0-3-inch	12.7	(0.7)	1.6	(0.3)	11.1	(0.8)	86.4	(2.2)
4	3+-inch YUM	29.8	(5.5)	22.3	(2.8)	7.5	(3.4)	21.9	(8.2)
9	3+-inch no-YUM	55.6	(5.4)	34.7	(5.5)	20.9	(3.1)	39.3	(5.6)
4	total YUM	66.9	(6.4)	35.4	(2.5)	31.5	(4.6)	46.5	(3.3)
9	total no-YUM	90.0	(4.5)	44.6	(6.6)	45.4	(4.2)	51.8	(5.5)

[1]One unit was excluded from the duff analysis due to apparent error in duff moisture sampling.

Table 5—Pearson's correlation coefficients between duff depth reduction, mineral soil exposure, diameter reduction, and other variables

Variable	Duff depth reduction	Percent duff reduction	Percent mineral soil	Diameter reduction
Duff depth reduction	1.0	—	—	—
Percent duff reduction	[1].65	1.0	—	—
Percent mineral soil exposure	[1].42	[1].79	1.0	—
Diameter reduction	.18	[1].61	[1].68	1.0
Preburn duff depth	[1].77	.03	−.11	−.18
Lower duff moisture	.15	.17	.25	−.28
Shallow duff moisture	[1]−.53	[1]−.45	[1]−.52	.10
Entire duff moisture (area weighted)	[1]−.38	[1]−.53	−.22	−.14
Entire duff moisture (volume weighted)	.23	.11	.18	−.29
NFDR 1,000-hour moisture	.26	.18	.29	−.43
Adjusted NFDR 1,000-hour moisture	.17	.08	.21	−.50
Large fuel moisture	−.35	[1]−.55	[1]−.59	[1]−.62
Large fuel loading/fuel moisture	−.02	.31	.32	[1].53
Small fuel consumption	[1].44	[1].39	.23	.17
Large fuel consumption	.22	[1].42	[1].42	[1].62

[1]Denotes significance at the $\alpha = 0.05$ level.

The best descriptive relationship for percentage duff consumption generated from the Deception Creek data was:

$$DR\% = 59.6 - 0.346\ DM + 7.066\ WR \quad (2)$$
$$(R^2 = 0.46, \text{ s.e.} = 8.4 \text{ percent})$$

where DR% = duff consumption, percent; DM = shallow duff moisture, percent; and WR = plot mean diameter reduction of large woody material, inches.

The presence of diameter reduction of large woody material in the Deception Creek equation suggests the importance of heat from surface fire in driving off duff moisture and increasing duff consumption. Consumption of large woody material has been found to be an important predictor of duff consumption in the Pacific Northwest (Little and others 1986; Ottmar and others 1985).

Duff depth reduction, unlike percentage duff consumption, was mostly overpredicted by equations in the literature. This apparent inconsistency is explained by the relatively complete consumption of a duff layer shallower than in those previous studies. Of the equations in previous work for predicting duff depth reduction, the best fit with Deception Creek data was obtained with Brown's 1985 equation, using average duff moisture content and preburn duff depth:

$$DR = 0.881 + 0.439\ PRE - 0.0096\ ADM \quad (3)$$
$$(R^2 = 0.72, \text{ s.e.} = 0.33)$$

where DR = duff depth reduction, inches; PRE = preburn duff depth, inches; and ADM = average duff moisture content, percent.

Predictions generated by this equation differed from observed values at Deception Creek by an average magnitude of 0.2 inch, with a bias of only 0.1 inch. Slightly better fit could be obtained with the coefficients generated specifically from Deception Creek data:

$$DR = 0.413 + 0.635\ PRE - 0.0094\ ADM \quad (4)$$
$$(R^2 = 0.70, \text{ s.e.} = 0.19 \text{ inch})$$

where DR = duff consumption, inches; ADM = average duff moisture, percent; and PRE = preburn duff depth, inches.

Mineral Soil Exposure—Mineral soil exposure averaged 66 percent following the prescribed fires (table 6, fig. 8). The thin layer of decomposing litterfall was largely consumed by fire. Mineral soil exposure was highly correlated with percentage of duff reduced (table 5) and, like percentage of duff reduced, was positively correlated with diameter reduction of large woody fuel and negatively correlated with moisture content of the shallow duff layer and the large woody fuel. Mineral soil exposure did not vary with depth of ground char, because most areas with light ground char probably had little preburn duff and litter and met the mineral soil criterion before the fires, and most areas with moderate or severe ground char had nearly complete duff consumption and mineral soil exposure. Much of the area where mineral soil was not exposed was incompletely burned pockets of deep rotten wood.

Of the equations in the literature for predicting mineral soil exposed by fire, the best fit with Deception Creek data was obtained with Brown's 1985 equation:

$$MSE = -8.98 + 0.899\ DR\% \quad (5)$$
$$(R^2 = 0.85, \text{ s.e.} = 11.7)$$

where MSE = mineral soil exposure, percent; and DR% = duff consumption, percent.

This equation fit the Deception Creek data with a bias of less than 1 percent, and an average deviation of 9 percent. Good fit was also obtained using the equation:

$$MSE = 167.4 - 31.6\ \ln(ADM) \quad (6)$$
$$(R^2 = 0.56, \text{ s.e.} = 16.7)$$

where MSE = mineral soil exposure, percent; and ADM = average duff moisture content, percent

Table 6—Mineral soil exposure, percent

Measurement	Mean	Std. dev.	Min.	Max.
Preburn:				
Ocularly on microplots	3	3	0	13
Based on 0.0 inch on spikes	9	9	0	45
Based on <0.4 inch on spikes	19	10	0	58
Postburn:				
Ocularly on microplots	47	16	7	86
Based on 0.0 inch on spikes	52	19	7	93
Based on <0.4 inch on spikes	66	17	15	98

from the same source. Bias of predictions with this equation averaged 2 percent, and average deviation was 15 percent. These equations predicted mineral soil exposed by fire essentially as well as any new equations generated from the data.

Woody Fuel—The fires burned nearly all the small woody fuel (fig. 10). Consumption averaged 94 percent for 0- to 1-inch fuel and 81 percent for 1- to 3-inch fuel. Consumption was not related to season of burn or treatment or to measured moisture content of any fuel component. Consumption of ¼- to 1-inch fuel was negatively correlated to NFDRS 100-hour fuel moisture but consumption of 1- to 3-inch fuel was not. Consumption of 1- to 3-inch fuel was positively correlated to consumption of ¼- to 1-inch fuel, duff depth consumption, and percentage of duff consumed.

Consumption of large woody material as measured with transects averaged 15.5 tons/acre. Transect intercept data actually showed an increase in large woody fuel loading following fires on several units. Probably logs concentrated at the tops of the units had rolled down into the units during the burns. Consumption of large woody material was not correlated with measured moisture or NFDR indices. It did not vary with season or YUM treatment. Residual fuel loadings of large woody material varied with preburn fuel loading and were significantly greater in no-YUM units than in YUM units ($p = 0.036$).

Unit average percentage of large woody material consumed as estimated from transect data averaged 5 percent greater than that estimated from wired logs. This difference was significant at the 0.05 probability level. Estimates from the wired logs should be more accurate than from the transects, because the problem of logs rolling onto or off the transects during burning is eliminated. Although the difference is statistically significant, transect data appear to provide estimates close enough to that of the wired logs for many applications.

On an individual piece basis, reduction of diameter and volume of large logs by fire was highly variable and only weakly related to preburn diameter, moisture content, presence or absence of bark, distance from the ground, or distance to nearest neighboring log. Consumption of rotten material was greater than sound, although it was much wetter. Moisture content of rotten logs averaged 31 percent higher than sound logs, and average diameter reduction was 1.6 inches greater. Totally rotten pieces burned more completely than partially rotten pieces (fig. 12).

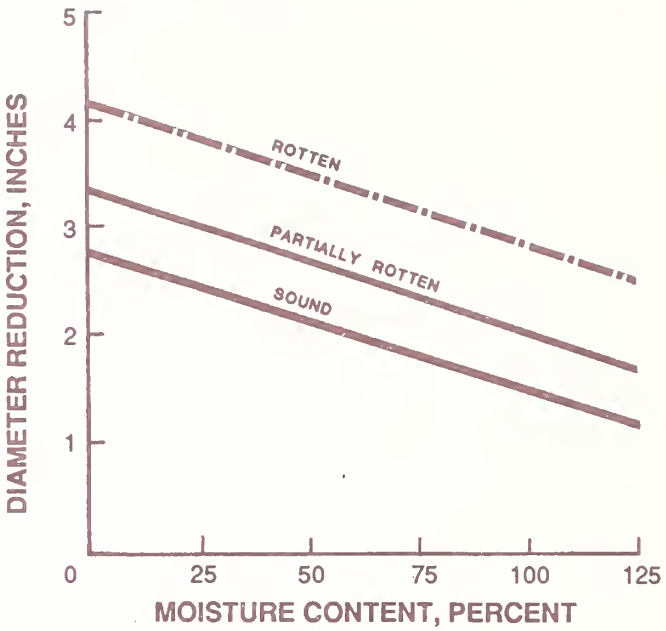

Figure 12—Diameter reduction related to percent moisture content and quality. Groups were significantly different at $\alpha = 0.10$.

Table 7—Diameter reduction (inches) of 3+-inch woody material as measured with wires

	Mean	Std. Dev.	Min.-Max.
		Sound	
Spring	5.2	1.7	2.4 –9.2
Fall	7.1	2.3	3.9 –9.2
		Rotten	
Spring	5.5	1.6	3.4 –8.2
Fall	10.9	5.6	3.1 –18.6

Unit average diameter reduction of large woody material is summarized in table 7. Prediction of diameter reduction is reported in depth in Brown and others (in press). Average moisture content alone was not a good predictor of diameter reduction. The R^2 value for the regression of average diameter reduction on average moisture content for sound logs was only 0.15. Plot average preburn diameter, although only weakly correlated with diameter reduction (R^2 for the regression was 0.08), was an important predictor in combination with moisture content. Greater average diameter reduction was observed in plots with greater average preburn diameter (fig. 13). Our best prediction

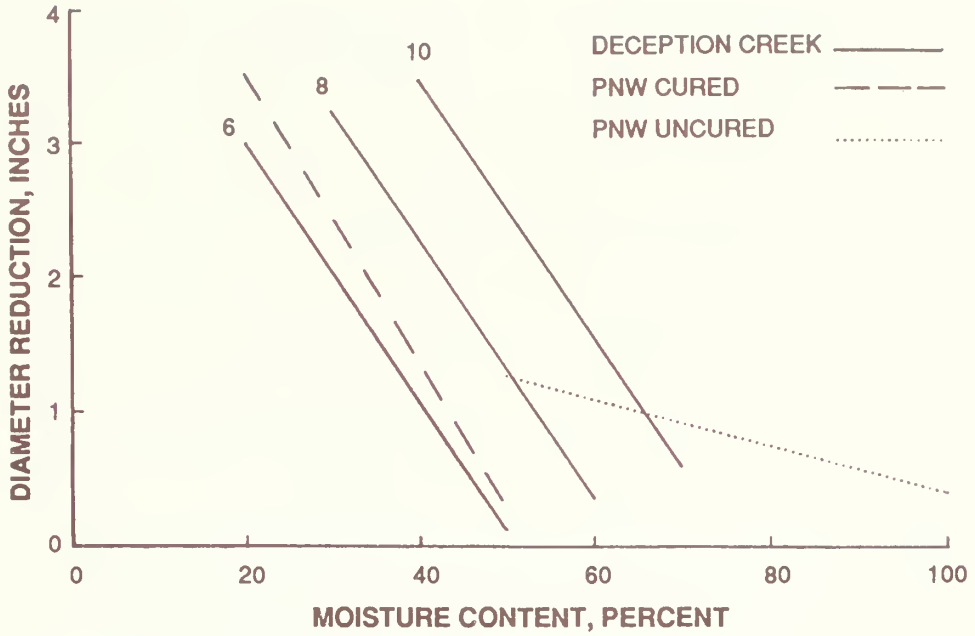

Figure 13—Diameter reduction of sound large woody fuel at Deception Creek based on the 18 wired units (equation 7) for unit average preburn diameters of 6, 8, and 10 inches, as compared to diameter-reduction equations developed for the Pacific Northwest (Ottmar 1987; Sandberg and Ottmar 1983).

equation for average diameter reduction of sound woody fuel was:

$$WR = 1.32 + 0.607\ DIA - 0.095\ MC \quad (7)$$
$$(R^2 = 0.65,\ \text{s.e.} = 0.52\ \text{inch})$$

where WR = diameter reduction of large woody material, inches; DIA = plot average preburn diameter of large woody material, inches; and MC = average moisture content of large woody pieces, percent.

Preburn diameter was an important variable at Deception Creek, perhaps because so many of the logs of all sizes burned completely. The presence of bigger logs that were completely consumed may have raised the plot average diameter reduction.

For sound and rotten fuels, the most precise prediction equation we found was:

$$WR = 3.75 + 0.392\ DIA - 0.093\ MC \quad (8)$$
$$(R^2 = 0.59,\ \text{s.e.} = 1.6\ \text{inches})$$

where WR = diameter reduction of large woody material, inches; DIA = plot average preburn diameter of large woody material, inches; and MC = average moisture content of large woody pieces, percent.

Severity—Most of the burned area was classified as having moderate ground char: Litter, duff, and small woody materials were almost completely consumed, leaving a light-colored ash, but the mineral soil was not visibly altered. A small amount of the area had little duff or litter before the burns and experienced only light ground char. The surface of the ground appeared blackened, but many twigs and fragments of duff remained essentially unaltered by the fire. Another small part of the area near burned-out stumps or below large logs was classified as having deep ground char. In these areas, the surface of the mineral soil was reddened, and organic material in the mineral soil was blackened.

Depth of ground char appeared to be determined not by fuel moisture conditions but by preburn fuel loadings and characteristics: the presence of a continuous layer of duff and litter distinguished areas of moderate ground char from areas of light ground char; the presence of rotting stumps or piles of logs characterized areas of deep ground char.

On the microplots, YUM units had less mineral soil exposure and more unburned organic material than no-YUM units, perhaps because the additional yarding treatment disturbed the duff, possibly

mixing it with soil, and resulting in less continuous duff burnout. Mineral soil exposure was 41 percent on YUM units and 56 percent on no-YUM units, while unburned organic cover was 13 percent on YUM units and 6 percent on the no-YUM clearcut strips. This difference was significant at $\alpha = 0.10$. No plant cover remained on the burned areas (fig. 14). Nine of the units had discontinuous burns, with 0.5 to 43 percent of the area unburned. These unburned patches were the only places with plant cover immediately postfire. Amount of unburned area averaged 4 percent for spring burns and 0 percent for fall burns; 6 percent for YUM units and 1 percent for no-YUM units.

MANAGEMENT CONSIDERATIONS

Duff and woody fuel consumption must be regulated for successful prescribed burning. Too little duff consumption may result in inadequate site preparation for regeneration, while too little woody fuel consumption may leave the site lacking in desirable microsites for natural or artificial regeneration, or at an unacceptable level of fire hazard. Conversely, excessive duff or woody fuel consumption may lead to degradation of site quality.

We recommend the postburn fuel loadings in figure 15 as acceptable for meeting the objectives of site preparation, site protection to maintain long term productivity, and fuel hazard reduction. The regions of the graph where the bars overlap represent desired residual loadings. These are general guidelines that apply to the mixed conifer type of the Northern Rocky Mountains. Specific fuel consumption and residual organic material objectives need to be determined for a particular prescribed fire project by evaluating resource objectives and trade-offs on that particular site. The range of acceptable loadings was based on experience with silvicultural and hazard reduction activities and published recommendations. A desirable range of 45 to 75 percent residual duff for site preparation and protection corresponds to duff consumption of 25 to 55 percent, and mineral soil exposures ranging from 15 to 40 percent (equation 5). The desirable range of residual duff is primarily determined by the need to maintain desirable conditions for mycorrhizal activities and nutrient cycling and storage, and to minimize risk of soil movement. A wide range in residual duff is acceptable for hazard reduction and site preparation objectives. Although large quantities of duff help sustain fire and can present fire-holding difficulties, the flammibility of duff by itself is low. A wide range in residual duff is considered acceptable for site preparation because the generally shallow duff

Figure 14—A clearcut unit following burning.

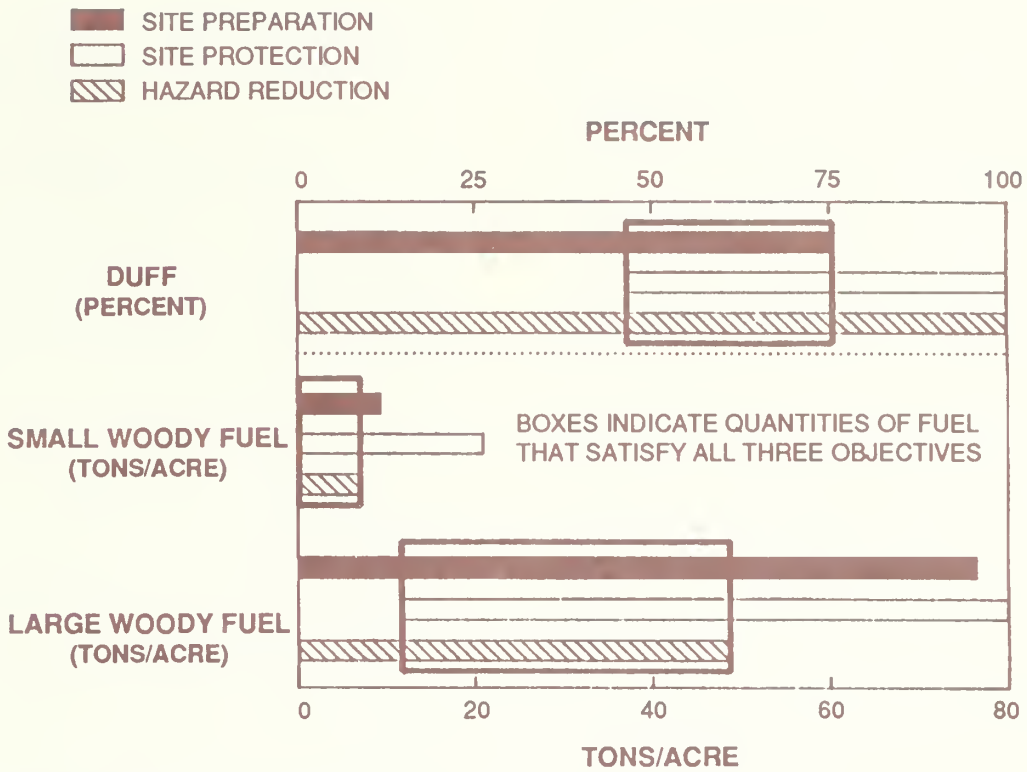

Figure 15—Recommended ranges of acceptable residual duff (percent) and woody fuel loadings (tons/acre) for site preparation and protection, and hazard reduction objectives. The regions of the graph where the bars overlap represent desired residual loadings.

profile, when at least partially burned, is a good germination medium and will continue to decay, thereby allowing adequate seedling establishment.

Small woody fuel should generally be reduced to a maximum of 8 to 10 tons/acre to meet hazard reduction objectives. These loadings correspond to fire intensities exceeding the limits of direct attack under moderate and severe fire weather conditions (Puckett and others 1979). For site preparation objectives these small woody fuels need to be reduced to not more than about 7 tons/acre to provide adequate planting sites and microsites for natural regeneration.

At least 10 tons/acre of large woody fuels need to be retained to provide for long-term site productivity (Harvey and others 1987). The amount of large woody fuel that constitutes a fuel hazard varies from site to site, depending on size distribution and other factors such as values at risk, surrounding fire behavior potential, and suppression capability (Brown 1980). If the large woody fuel is mostly in the 4- to 6-inch diameter range, 30 tons/acre may constitute an unacceptable fire hazard. At Deception Creek the large woody material was fairly large (average preburn diameter 8 inches for sound, 10 inches for rotten material), so reducing the large woody fuel loading to 50 tons/acre or less met fuel hazard reduction needs. Very high loadings of large woody fuel can present an impediment to both natural and artificial regeneration.

For the most part, the prescribed fires at Deception Creek accomplished the woody fuel consumption and retention objectives as outlined above. Duff consumption was greater than optimal, ranging from 29 to 93 percent and averaging 64 percent. Twenty-five of the units, or 70 percent, exceeded the recommended maximum duff consumption. Residual loadings of small woody fuel ranged from 0.1 to 6 tons/acre, with a mean of 1.5 tons/acre. Only one unit had a residual loading greater than 5 tons/acre. Residual loadings of large woody fuels ranged from 9 to 82 tons/acre, with a mean of 31 tons/acre. Only one unit had a residual loading of small woody fuel greater than 5 tons/acre. Residual loadings of large woody fuels ranged from 9 to 32 tons/acre, with a mean of 31 tons/acre. Two units exceeded the recommended 50-ton maximum for large woody fuels, while one unit did not meet the recommended 10-ton minimum. Although

a large amount of fuel was consumed, remaining fuels were adequate to meet long-term site productivity guidelines.

Results indicate that it may be difficult to burn in this fuel type without consuming a large portion of the shallow duff layer and exposing considerable mineral soil. Consumption of duff was related to duff moisture content, indicating that an opportunity exists to control duff consumption by burning only under prescribed duff moisture conditions. But, under the range of operational conditions we encountered, much of the duff was consumed. The years covered by this study were characterized by hot, dry spring weather with little precipitation after snowmelt. Under moister seasonal weather patterns, prescribed burns may achieve less duff consumption. If retention of the shallow duff layer is an important objective, however, it may be necessary to conduct prescribed fires under marginal burning conditions so that discontinuous or "jackpot" burns are achieved. The deep pockets of rotten wood prevalent in this forest type retain moisture throughout the burning season; thus there is a broad period of time when prescribed fires will not damage this resource.

Prescription Development

When developing prescriptions for burning in this forest type, the following process may be helpful:

1. Identify the objectives for the prescribed fire project. These may include site preparation for natural or artificial regeneration and fire hazard reduction.
2. Determine desired residual fuel loadings, keeping in mind both the objectives identified in step 1, and the need to protect the long-term productivity of the site. Figure 15 may be used for this purpose, but specific targets need to be developed on an individual site basis.
3. Using estimated preburn fuel loadings and desired residual fuel loadings, determine target fuel consumption ranges.
4. Prescribe fuel moisture parameters. Figure 16 may be used to determine acceptable duff moistures. Where preburn large woody fuel loadings are high, as in this study, it may not be necessary to constrain large woody fuel moisture in the prescription. Adequate residual fuel loadings will probably be obtained under virtually all operational conditions. If it is necessary to constrain large woody fuel

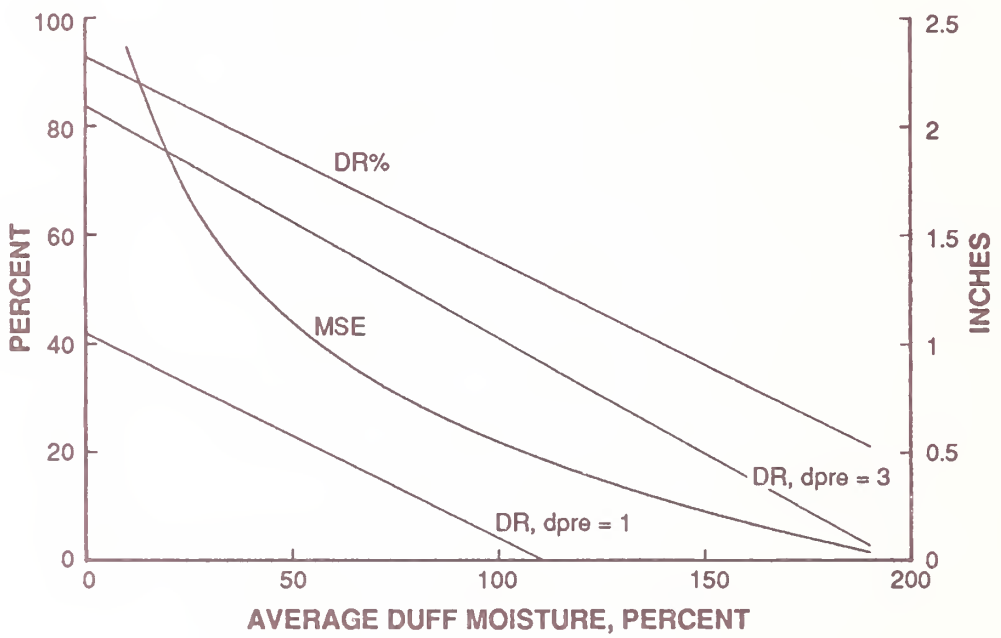

Figure 16—Relationships of duff depth reduction (DR, inches), percentage of duff consumed (DR%), and percentage of mineral soil exposed (MSE) to average duff moisture content. Duff depth reduction is shown for preburn duff depths (dpre, inches) of 1 and 3.

moisture content, use the following equations derived from equations 7 and 8:

For mostly sound fuel:

$$MC = 13.89 + 6.39\ DIA - 10.52\ DIA\ (1 - SQRT(1 - CONS/PRELG)) \quad (9)$$

where MC = moisture content of large woody fuel, percent; DIA = preburn average diameter of large woody fuel, inches; CONS = desired consumption of large woody fuel, tons/acre; and PRELG = preburn loading of large woody fuel, tons/acre.

For fuel that contains appreciable rotten material:

$$MC = 40.32 + 4.23\ DIA - 10.75\ DIA\ (1 - SQRT(1 - CONS/PRELG)) \quad (10)$$

where MC = moisture content of large woody fuel, percent; DIA = preburn average diameter of large woody fuel, inches; CONS = desired consumption of large woody fuel, tons/acre; and PRELG = preburn loading of large woody fuel, tons/acre.

Prediction Equations

Results from this study confirmed earlier duff and fuel consumption work for the most part. For predicting fuel consumption in this fuel type, equations previously published in Brown and others (1985) may be used. These equations have been reproduced in this paper as equation 1 for predicting percentage of duff reduced, equation 3 for predicting duff depth reduction, and equations 5 and 6 for predicting mineral soil exposure (fig. 16).

For predicting consumption of large sound woody fuel, use equation 7. For fuel types with considerable rotten material, equation 8 should be used. Both these equations predict diameter reduction. To convert to consumption in tons per acre, use the following calculation:

$$CONS = PRELG(1 - ((DIA - WR)/DIA)^2) \quad (11)$$

where CONS = large woody fuel consumption, in tons/acre; PRELG = preburn large woody fuel loading, tons/acre; DIA = preburn average diameter of large woody fuel, inches; and WR = predicted diameter reduction of large woody fuel from equation 7 or 8, inches.

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			Preburn fuel loadings				Moisture contents								Fuel consumption				
Unit	Burn date	Duff[1] depth	0-1-inch	1-3-inch	3+-inch sound	3+-inch rotten	0-¼-inch	¼-1-inch	Litter-based duff	Deep rotten wood	3+-inch sound	3+-inch rotten	NFDRTH	Min. soil exp.[2]	Duff depth	0-1-inch	1-3-inch	3+-inch	Diameter reduction of 3+-inch from wire
		Inches	*Tons/acre*				*Percent*								*Inches*	*Tons/acre*			*Inches*
3	9/05/84	1.94	6.43	5.55	5.22	13.26	14	15	24	176	—	—	11	38	1.10	5.89	2.80	3.95	—
5	9/04/84	1.70	5.72	8.72	8.26	32.58	10	14	18	82	—	—	11	71	1.16	5.64	8.22	12.75	—
6	9/04/84	2.52	5.58	5.80	25.85	11.93	10	14	19	132	—	—	11	64	1.28	5.44	4.69	13.65	—
7	6/26/85	2.54	5.31	9.17	24.78	12.85	9	10	24	125	—	—	22	65	1.76	5.28	7.73	8.15	—
8	6/26/85	2.16	5.67	5.66	34.82	16.84	9	9	16	210	48	111	22	57	1.49	4.77	4.21	23.82	1.25
9	6/25/85	2.55	4.19	5.33	14.30	21.46	13	9	18	126	—	—	23	62	1.39	4.19	4.76	6.13	—
12	6/25/85	1.44	3.88	4.80	6.24	29.93	19	17	32	171	—	—	23	56	.42	1.81	.87	12.60	—
13	6/25/85	2.09	5.34	9.51	31.02	22.81	11	10	14	217	—	—	23	71	1.40	5.09	8.54	28.64	—
14	6/27/86	1.56	5.10	5.89	17.90	22.85	11	11	15	243	45	95	24	91	1.19	4.37	4.97	12.14	2.29
15	6/25/85	2.42	4.71	5.12	32.48	12.92	9	9	—	—	38	96	23	61	1.43	4.51	4.71	12.66	2.11
16	6/25/85	2.04	5.28	6.18	19.05	8.91	10	9	17	154	49	104	23	62	1.36	5.01	4.80	3.33	1.24
17	6/25/85	1.91	3.65	5.70	8.86	9.92	9	9	13	228	—	—	23	64	1.12	3.43	4.26	9.43	—
18	6/25/85	1.68	2.93	4.68	32.84	5.76	8	7	15	205	46	96	23	64	.90	2.80	3.73	10.10	2.03
19	8/28/85	1.75	5.99	6.93	42.62	8.31	9	11	18	172	35	55	17	93	1.63	5.99	6.85	32.85	3.95
20	8/28/85	1.76	6.84	9.39	21.98	12.07	11	25	19	178	32	61	17	89	1.48	6.79	8.89	19.67	4.32
21	6/26/85	1.85	4.80	8.73	23.25	12.37	9	8	10	300	39	61	22	59	1.02	4.73	6.72	10.87	2.06
24	9/04/84	1.42	7.63	6.93	5.48	16.87	11	17	29	176	—	—	11	61	.71	6.93	5.65	[3]–.22	—
25	9/05/84	1.62	4.32	4.54	44.74	15.27	15	16	27	80	39	81	11	83	1.17	3.80	3.85	25.85	3.66
27	6/27/86	1.31	3.82	6.24	46.28	11.49	10	13	16	201	53	70	24	85	.98	3.34	4.78	30.67	3.54
28	6/27/86	1.27	3.96	5.62	49.33	4.23	10	13	16	201	55	85	24	69	.87	3.72	4.97	14.32	2.67
30	6/27/85	—	5.83	7.05	49.05	13.21	11	13	15	268	—	—	22	—	—	5.70	6.31	–19.85	—
31	6/27/85	1.55	5.23	5.74	55.02	13.57	11	13	15	268	—	—	22	73	.94	5.23	5.19	28.21	—
32	9/19/84	1.62	5.67	5.87	57.23	10.92	12	14	38	130	—	—	15	54	.89	5.44	4.17	23.07	—
33	9/19/84	1.60	4.15	4.87	62.29	14.74	18	16	37	150	—	—	15	29	.68	4.12	2.69	13.94	—
34	6/27/85	2.27	7.81	7.76	56.79	11.16	11	13	15	268	35	86	22	71	1.59	7.64	7.11	36.96	2.20
35	6/27/85	1.63	5.86	7.71	45.34	5.53	11	13	15	268	50	69	22	72	1.08	5.86	7.35	12.93	1.80
36	9/19/84	1.18	6.36	8.42	48.05	9.92	12	14	38	130	55	73	15	59	.63	5.28	6.55	16.46	1.64
37	9/19/84	1.40	4.67	5.85	56.18	9.46	12	14	38	130	54	55	15	67	.99	4.02	4.83	35.78	3.54
38	6/27/85	1.96	3.83	4.80	35.83	9.00	11	11	16	206	—	—	22	65	1.29	3.67	4.04	15.55	—
39	6/27/85	2.42	5.69	9.76	31.34	13.49	11	11	16	206	—	—	22	76	1.73	5.66	9.42	23.15	—
40	6/27/85	2.26	4.57	5.57	35.35	7.81	11	11	16	206	53	72	22	79	1.80	4.51	4.55	14.10	2.27
41	6/27/85	1.27	4.49	5.61	40.23	6.93	11	11	16	206	51	50	22	79	.98	4.49	4.86	9.06	1.69
42	9/19/84	1.16	5.14	7.38	54.67	6.26	14	15	40	100	61	68	15	64	.70	4.74	5.64	12.10	1.87
43	9/19/84	2.10	6.67	9.83	20.77	5.23	14	15	40	100	—	—	15	41	1.00	6.28	8.74	8.70	—
44	6/27/85	1.83	5.26	7.44	36.67	12.68	11	11	16	206	—	—	22	76	1.31	5.16	6.09	15.16	—
45	6/27/85	1.96	4.75	4.84	35.70	8.01	11	11	16	206	—	—	22	71	1.17	4.75	3.68	20.61	—

[1]From spike data.
[2]Based on <0.4-inch residual duff criterion.
[3]Negative values for consumption are due to sampling error or to logs rolling across the fuel transects during burning.

APPENDIX 2: ERROR IN FUEL MOISTURE CONTENT ESTIMATION

Number of samples required for estimating moisture content within a 20 percent error at a 95 percent confidence level (fig. 17):

Fuel	Sample size
1-hour (0-¼-inch)	5
10-hour (¼-1-inch)	7
Rotten wood duff	25
Litter-derived duff	30
Sound 3+-inch logs	40
Rotten 3+-inch logs	50

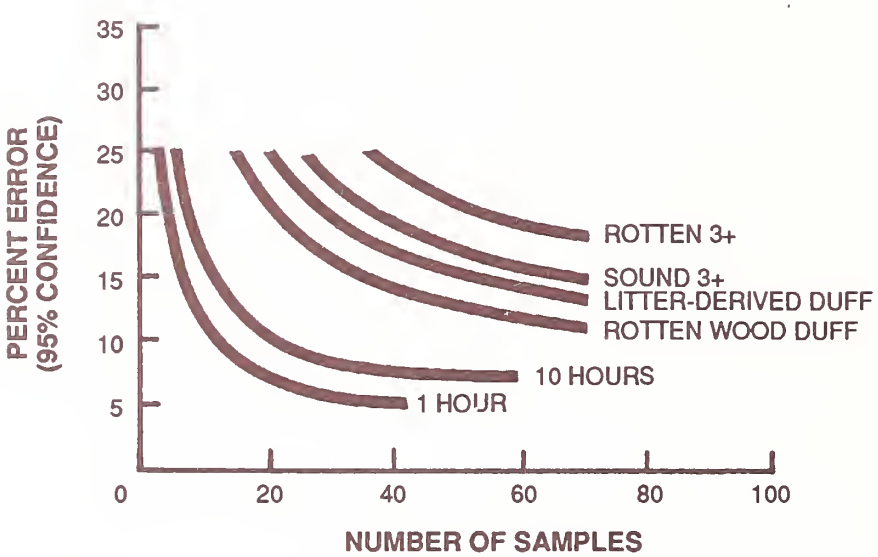

Figure 17—Relationship of percentage of error to sample size for moisture content estimation of several categories of fuel sampled at Deception Creek.

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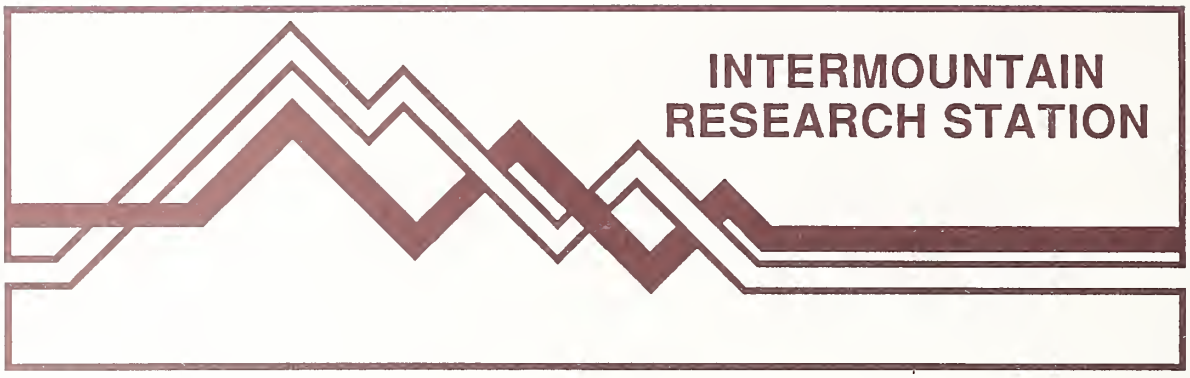
Reinhardt, Elizabeth D.; Brown, James K.; Fischer, William C.; Graham, Russell T. 1991. Woody fuel and duff consumption by prescribed fire in northern Idaho mixed conifer logging slash. Res. Pap. INT-443. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 22 p.

Describes results of prescribed burning 36 plots in northern Idaho mixed conifer logging slash. Fuel characteristics and methods for predicting duff and woody fuel consumption are reported. Guidelines are included for developing fire prescriptions.

KEYWORDS: site preparation, fuel hazard reduction, fuel moisture, fire effects



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